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OTV FLUID MANAGEMENT SYSTEMS

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Design, performance, and technology issues associated with reduced gravity propellant management for Orbital Transfer Vehicles (OTV's) have been reviewed. The inspace cryogenic management state-of-technology will significantly affect the overall confidence level associated with a resupply mission and propulsion performance. Thus, although mission requirements are frequently used to determine technology requirements, it is also apparent that technology availability drives mission requirements. Cryogen resupply sequences, timelines, controls, and associated crew involvement are all affected by the technology state. Additionally, OTV propellant tankage configurations, tankage thermodynamic conditions, acceleration environment, propulsion interfaces, and instrumentation are significant factors. Basic propellant transfer phases examined that drive orbital servicing requirements include: (1) tankage preconditioning (purging, venting, etc.), (2) tankage chilldown, and (3) propellant fill. Propellant management support of the OTV propulsion phases includes engine restart requirements (pressurization, chilldown, burn duration, etc.) and orbital coast between engine burns. Technology activities in support of identified technology issues are reviewed.

SPACE-BASED OTV PROPELLANT REQUIREMENTS

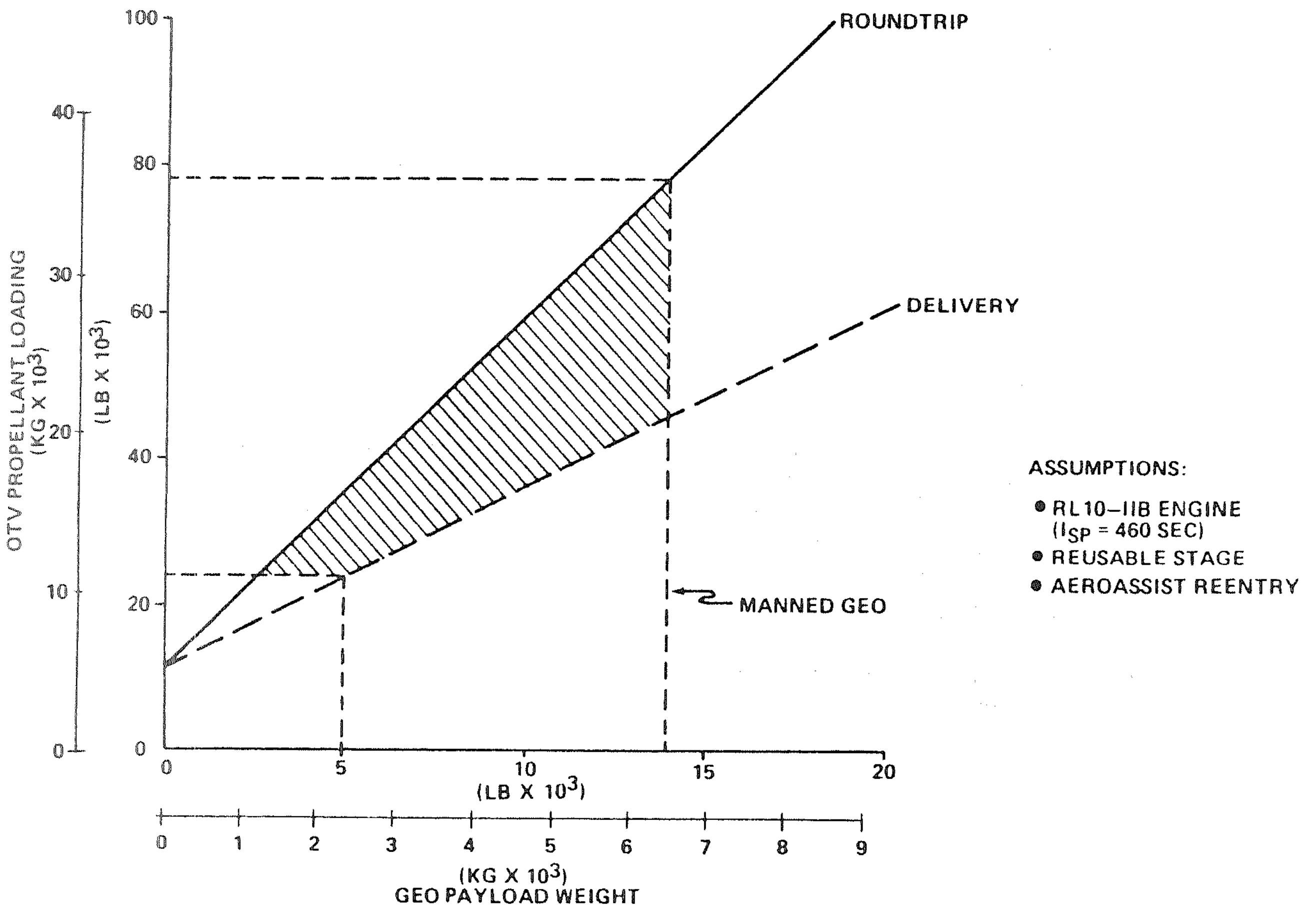


Figure 1

The average payload weight required to be transported from LEO to GEO will be in the range of 5,000 to 14,000 pounds. The upper range of payloads is normally associated with manned GEO roundtrip missions. The resultant propellant requirements, based on these payload weights, ranged from approximately 24,000 to 78,000 pounds. The chart on the opposite page graphically portrays these requirements.

OTV CRYOGENIC MANAGEMENT CONSIDERATIONS

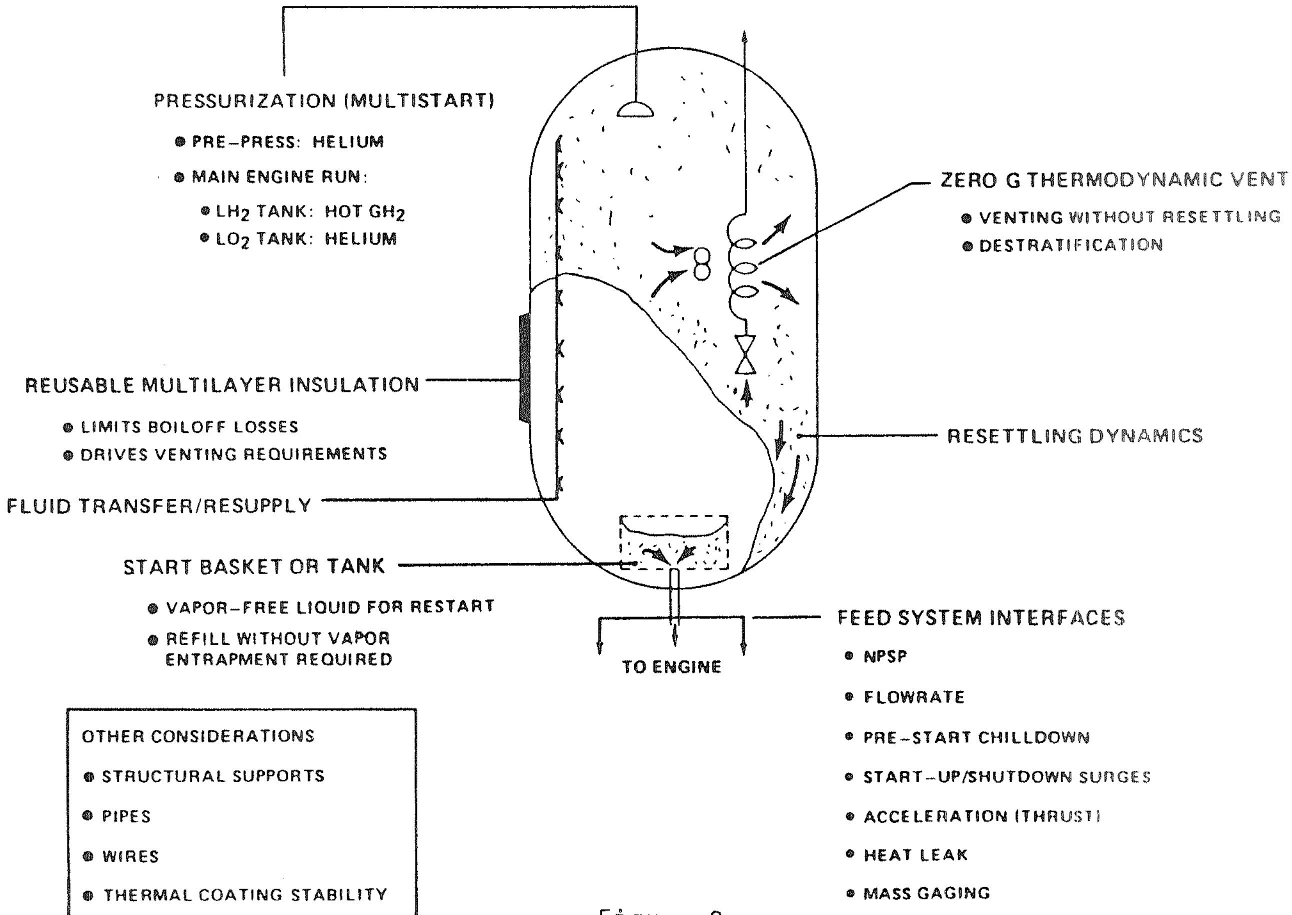


Figure 2

Fluid management of an OTV will require component, subsystem, and system development emphasis. The chart on the opposite page pictorially shows the major areas that must be addressed in the design of a cryogenic OTV. Some of the major issues involved in the design are no-liquid venting, stratification, vapor entrapment in the start basket, engine feed system requirements and reusability. Several items will require orbital testing for verification of their performance (e.g. thermodynamic vent, fluid dynamics, start basket, fluid transfer, etc.). Also, it is important to note that the thermodynamic, fluid mechanic and heat transfer interactions between components and subsystems must be addressed/understood to assure proper system integration. For example, the zero G vent system design is driven by heat leak control/distribution. Similiarly, the start basket liquid retention capability is degraded by increases in feed system heat leak, pressurization gas temperature, and propellant temperature. Engine system re-start/run requirements on propellant conditions significantly affect thermodynamics within the tank and start basket design.

OTV CRYOGENIC MANAGEMENT CONSIDERATIONS

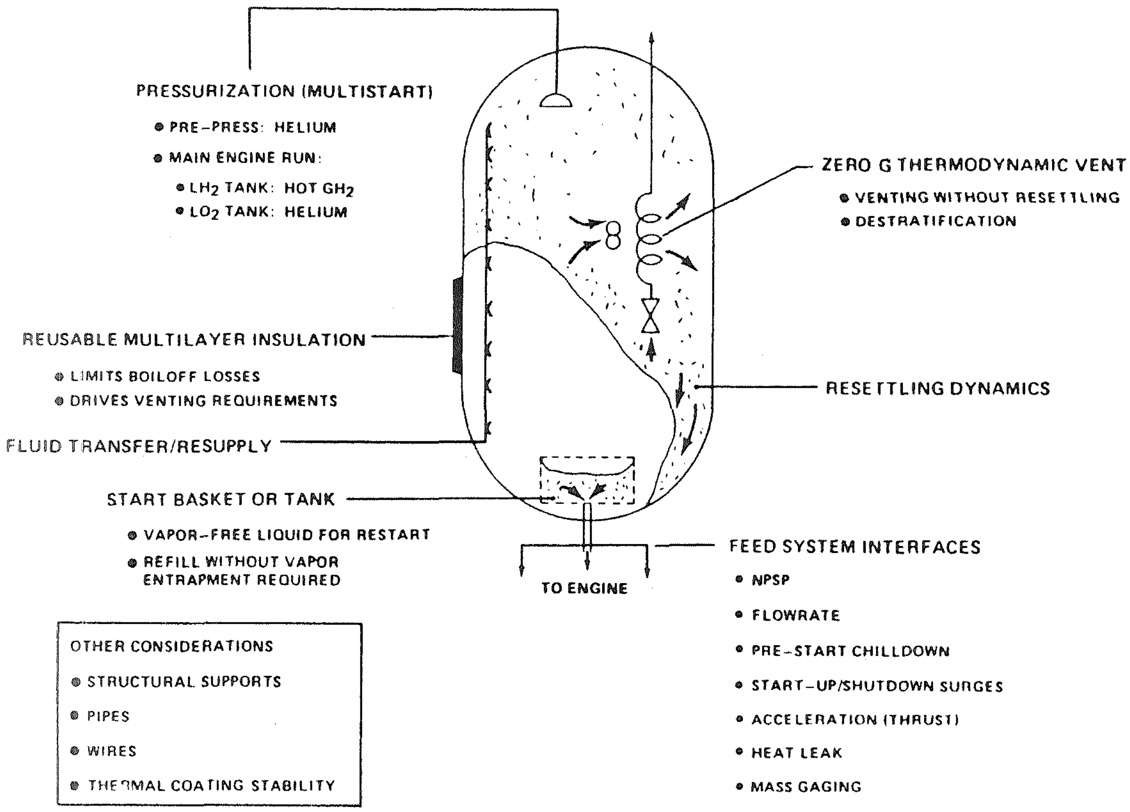


Figure 3

Fluid management of an OTV will require component, subsystem, and system development emphasis. The chart on the opposite page pictorially shows the major areas that must be addressed in the design of a cryogenic OTV. Some of the major issues involved in the design are no-liquid venting, stratification, vapor entrapment in the start basket, engine feed system requirements and reusability. Several items will require orbital testing for verification of their performance (e.g. thermodynamic vent, fluid dynamics, start basket, fluid transfer, etc.). Also, it is important to note that the thermodynamic, fluid mechanic and heat transfer interactions between components and subsystems must be addressed/understood to assure proper system integration. For example, the zero G vent system design is driven by heat leak control/distribution. Similiarly, the start basket liquid retention capability is degraded by increases in feed system heat leak, pressurization gas temperature, and propellant temperature. Engine system re-start/run requirements on propellant conditions significantly affect thermodynamics within the tank and start basket design.

ORBITAL CRYOGEN TRANSFER CONSIDERATIONS

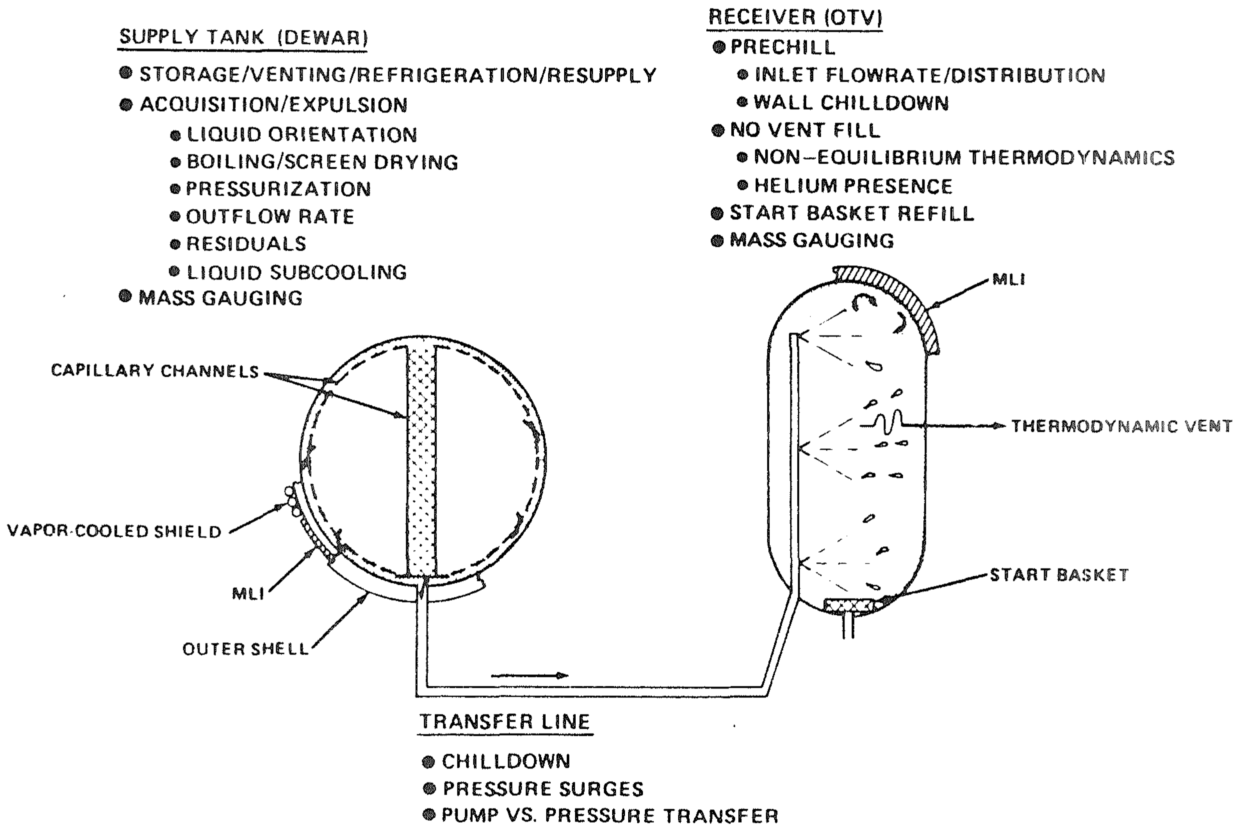


Figure 4

One of the primary fluid management requirements will be the transfer of both LOX and LH_2 in a zero-g environment. Both filling of the OTV tanks and delivery of the propellant to the engine must be considered. The chart on the opposite page describes the major areas that must be investigated. The supply tank could be an orbital storage facility located at the Space Station. The receiver tank would be the OTV LOX and LH_2 tank. Primary issues to be addressed on the OTV are tank prechill, vent vs. no-vent fill, start basket refill and mass gauging. Other areas requiring study are transfer line pressure and temperature transients and pump versus pressure fed fluid transfer.

OTV TANK INSULATION EFFECTS ON VEHICLE PERFORMANCE

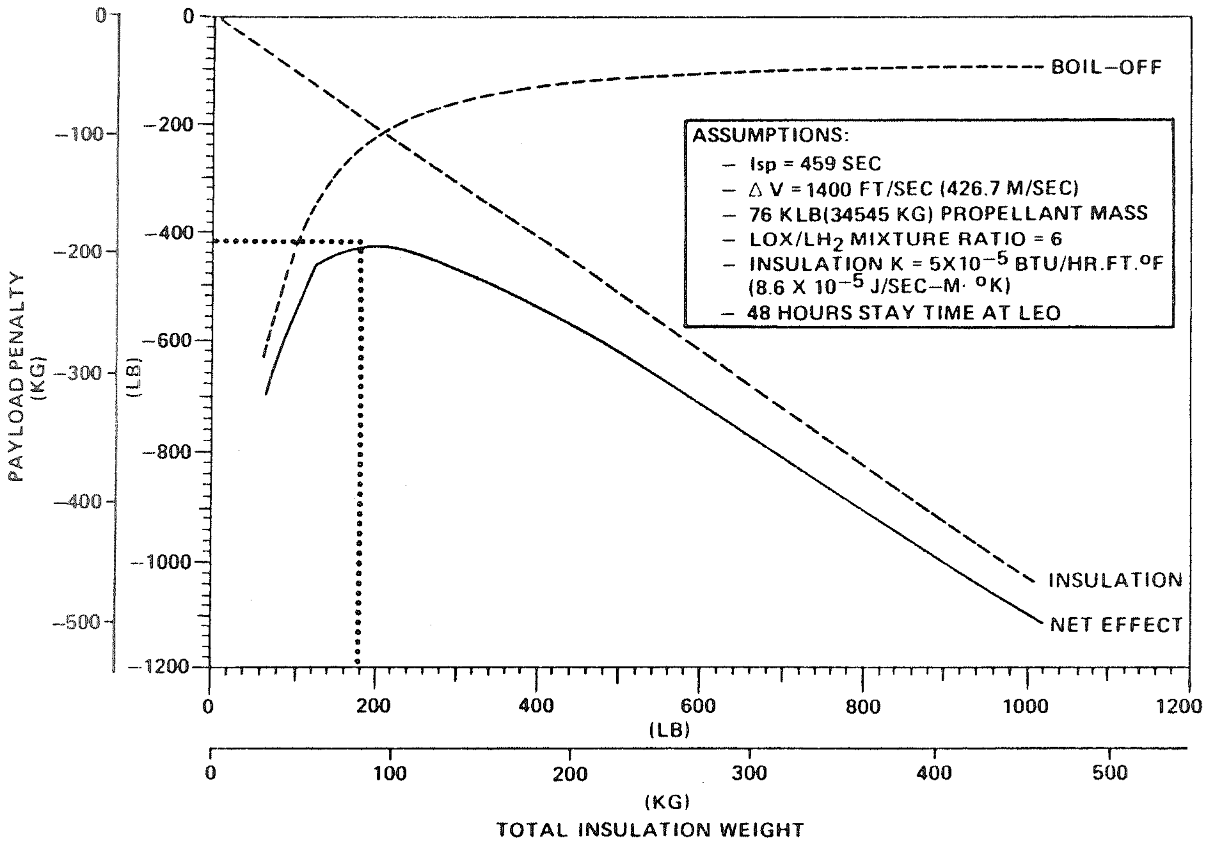


Figure 5

The design of the insulation system for both the hydrogen and oxygen tanks on a space based OTV will be optimized to provide maximum payload delivery capability to GEO. A tradeoff between insulation weight and propellant boiloff provides a characteristic curve such as shown on the opposite page. The design optimization is dependent on how much time after propellant loading will be required at LEO, during transfer from LEO to GEO and at GEO. Since the environment at LEO is generally warmer than at GEO and assuming equal stay times at both LEO and GEO, the LEO environment would dictate the insulation design. Based on the assumptions specified, a total insulation weight of 180 lb would be optimum.

OTV TANK INSULATION REQUIREMENTS

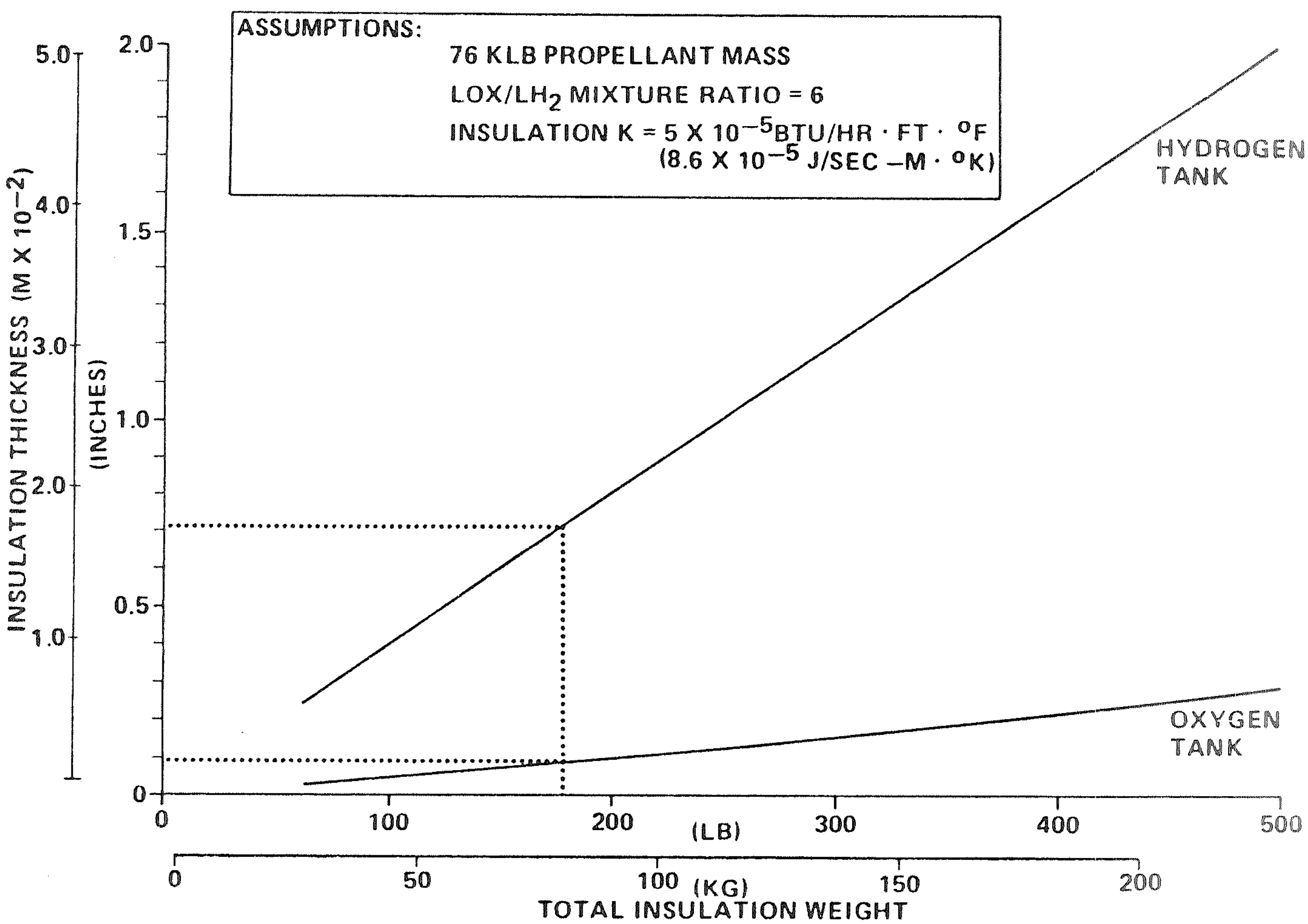


Figure 6

Based on the assumptions made on the previous page, the insulation requirements for both the hydrogen and oxygen tank are shown in the graph on the facing page. As indicated, based on an optimum total insulation weight of 180 lb, the resultant insulation thicknesses for the hydrogen and oxygen tank are approximately 0.7 and 0.1 inches, respectively. The insulation thicknesses on each tank are tailored to maintain the proper propellant mixture ratio.

OTV LH_2 TANK PRESSURES DURING ORBITAL COAST STRATIFICATION/MIXING EFFECTS

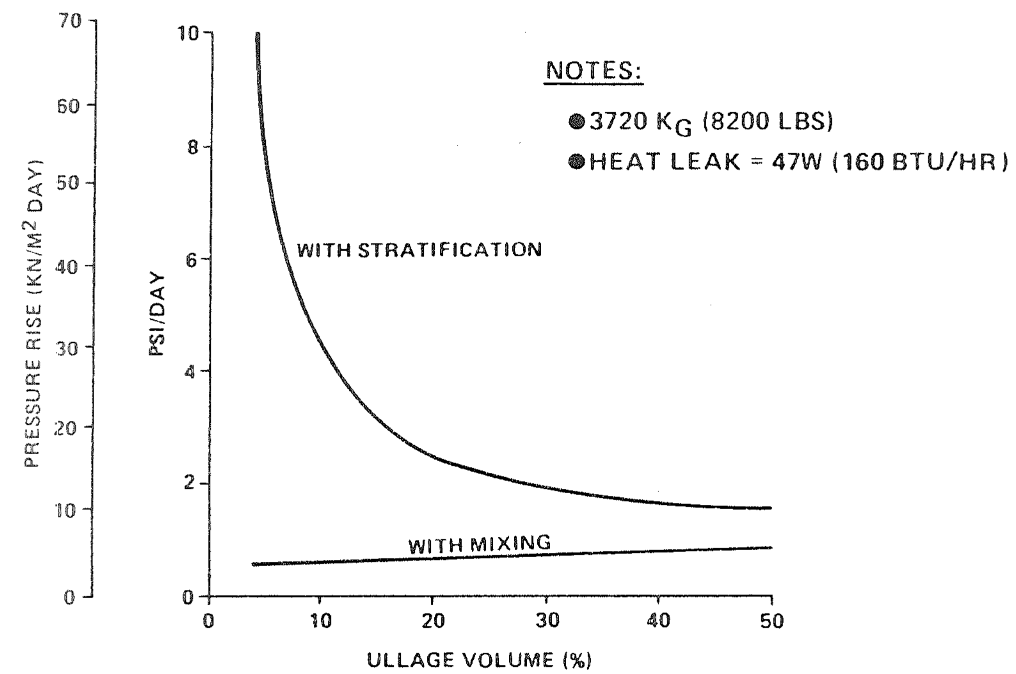


Figure 7

Propellant conditions during orbital coast periods between engine burns are important from several standpoints. For example, tankage heat leak and its distribution within the propellant determines the ullage pressure rise rates and resultant vent rates/cycling. To minimize pressure rise rate and transient thermodynamic uncertainties, the general approach is to assure that tankage sidewall and penetration heat leak is uniformly distributed within the bulk liquid, and that good heat exchange between the ullage and liquid exists. To remove uncertainties associated with passive mixing/destratification in reduced gravity, active mixing techniques are generally employed in OTV concept designs.

Additionally, the energy distribution within the tank can significantly affect other subsystem functions. If a capillary start basket is utilized, localized stratification within and near the basket should be prevented, i.e., localized superheating/boiling can occur. Also, proper feed system thermodynamic conditions must be established for each engine burn.

OTV LO_2 TORUS TANKS
PROPELLANT MANAGEMENT TECHNOLOGY ISSUES

- NO IN-FLIGHT EXPERIENCE WITH REDUCED GRAVITY FLUID/HEAT TRANSFER BEHAVIOR IN TORUS TANKS.
- ACQUISITION DEVICE R&D REQUIRED
  - PROPELLANT SETTLING
  - THERMAL ISOLATION
  - RESIDUALS
  - ORBITAL PERFORMANCE VERIFICATION
- PRESSURIZATION/VENTING
  - MULTIPLE ENGINE RESTARTS/PRESSURIZATION EFFICIENCY
  - ZERO G VENTING
  - STRATIFICATION/DESTRATIFICATION
  - ACQUISITION SYSTEM INTERFACES
- SLOSH
  - PROPELLANT C. G./VEHICLE CONTROL
  - BAFFLES
- INSULATION
  - UNIQUE TANK SHAPE EFFECTS ON PERFORMANCE
  - PURGE

Figure 8

The state-of-technology supporting LO_2 fluid management in torus tanks is weak. Due to its unique geometry, the torus shape introduces a wide range of issues that have not been addressed in past technology efforts. Propellant acquisition, pressurization, venting, stratification/destratification, sloshing, insulation, and heat leak distributions are all areas requiring R&D efforts specifically applicable to torus tanks.

TANK PRE-CHILL PREPARATIONS SUMMARY

- DILUTION OF HELIUM RESIDUALS PRIOR TO REFUELING REQUIRED TO PREVENT:
  - EXCESSIVE PRESSURES AT END OF FILL
  - INACCURATE KNOWLEDGE OF PROPELLANT VAPOR PRESSURES
  - START BASKET HELIUM ENTRAPMENT
  - INACCURATE THERMODYNAMIC MASS GAUGING
- APPROXIMATE DILUTION LEVELS REQUIRED
  - $LH_2 \leq$ .45 KG (1 LBS)
  - $LO_2 \leq$ .09 KG (.2 LBS)

  } FURTHER DILUTION REQUIRED IF THERMODYNAMIC MASS GAUGING UTILIZED
- PROCEDURAL/TECHNOLOGY CONCERNS
  - DURATION OF VENT/HOLD CYCLES
  - KNOWLEDGE OF HELIUM RESIDUAL MAGNITUDE

Figure 9

The initial phase of orbital transfer is "prechill preparations." If no helium pressurant gases have been used in the tankage to be filled, the prechill preparations would be minimal. However, if helium is present then the tankage must be purged and vented until the helium is reduced to an acceptable level. The "acceptable level" is determined based on end-of-fill pressures/achievement of maximum fill control, capillary screen acquisition system pressure, and thermodynamic mass gaging (if used). The LO_2 system sensitivity to helium is significantly greater than with LH_2. Lack of orbital experience and in-orbit measurement of residual helium magnitudes are the primary concerns in developing a suitable purge approach.

TANK PRE–CHILL PREPARATIONS SUMMARY

- DILUTION OF HELIUM RESIDUALS PRIOR TO REFUELING REQUIRED TO PREVENT:
  - EXCESSIVE PRESSURES AT END OF FILL
  - INACCURATE KNOWLEDGE OF PROPELLANT VAPOR PRESSURES
  - START BASKET HELIUM ENTRAPMENT
  - INACCURATE THERMODYNAMIC MASS GAUGING
- APPROXIMATE DILUTION LEVELS REQUIRED
  - LH_2 < .45 KG (1 LBS)
  - LO_2 < .09 KG (.2 LBS)

  } FURTHER DILUTION REQUIRED IF THERMODYNAMIC MASS GAUGING UTILIZED
- PROCEDURAL/TECHNOLOGY CONCERNS
  - DURATION OF VENT/HOLD CYCLES
  - KNOWLEDGE OF HELIUM RESIDUAL MAGNITUDE

Figure 10

The initial phase of orbital transfer is "prechill preparations." If no helium pressurant gases have been used in the tankage to be filled, the prechill preparations would be minimal. However, if helium is present then the tankage must be purged and vented until the helium is reduced to an acceptable level. The "acceptable level" is determined based on end-of-fill pressures/achievement of maximum fill control, capillary screen acquisition system pressure, and thermodynamic mass gaging (if used). The LO_2 system sensitivity to helium is significantly greater than with LH_2. Lack of orbital experience and in-orbit measurement of residual helium magnitudes are the primary concerns in developing a suitable purge approach.

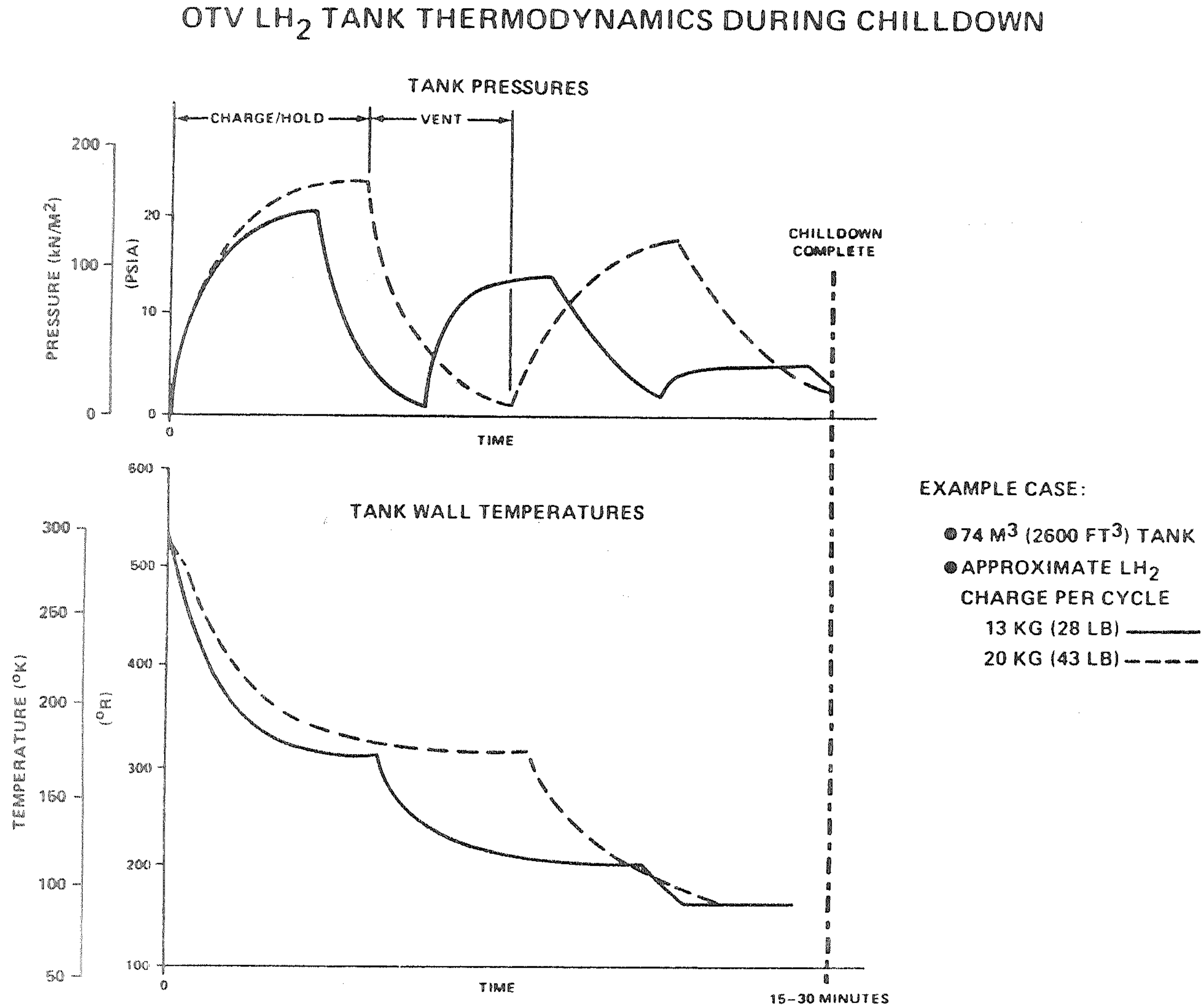


Figure 11

Childown is accomplished by introducing propellant into a tank in such a manner that good heat exchange between the high temperature walls and chilldown liquid is assured. Thermodynamic calculations indicate that the amount of propellant required to chill a tank should be relatively small. It is therefore doubtful that chilldown procedure selection will be driven by minimization of chilldown liquid. However, the complicated thermodynamic, boiling heat transfer, and fluid dynamic phenomena involved cannot be analytically modeled with confidence. Hence, issues involving definition of inlet flow distribution/velocity, charge/hold duration and maximum pressure, vent duration, and instrumentation to monitor chilldown progress remain.

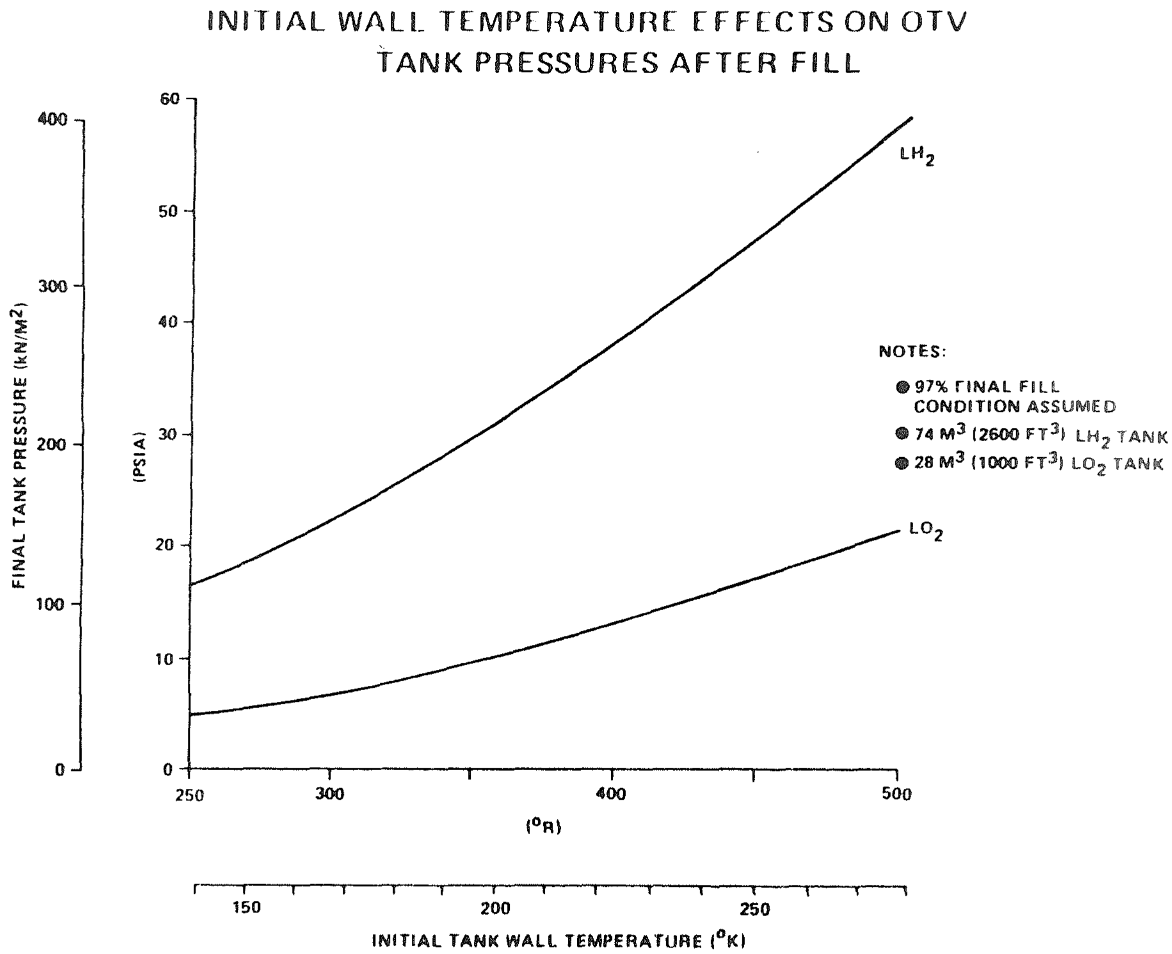


Figure 12

Receiver tank chilldown must be conducted whenever thermal energy stored in the tank walls is sufficient to preclude a nonvented fill operation. For example, with initial wall temperatures of 450°R, the LH_2 and LO_2 tanks final pressures would be 48 psia and 18 psia, respectively; hence, LH_2 chilldown would be required, whereas LO_2 chilldown would be optional. A LH_2 tank wall temperature of less than 250°R probably will be required.

TRANSFER LINE/TANK CHILLDOWN SUMMARY

- REQUIREMENT: REDUCE TRANSFER LINE/TANK WALL TEMPERATURES SUFFICIENTLY TO PREVENT EXCESSIVE LINE PRESSURE/FLOW SURGES AND TO ENABLE A NON–VENTED TANK FILL
- PROCEDURAL/TECHNOLOGY CONCERNS:
  - TANK CHARGE/HOLD/VENT CYCLE DEFINITION
    - SEMI–EMPIRICAL MODELING LACKS EXPERIMENTAL DATA
    - LACK OF HARDWARE EXPERIENCE
    - WALL CHILLDOWN CRITERION: CURRENT RANGE = 95°K TO 200°K (170°R TO 360°R)
    - CHARGE MASS/FLOWRATE SELECTION TBD
  - LACK OF TRANSFER LINE CHILLDOWN EXPERIENCE – PREVENTION OF EXCESSIVE SURGES AND LINE LOADS
  - INSTRUMENTATION TO MONITOR CHILLDOWN PROCESS

Figure 13

Based on the preceding discussions of chilldown issues, optimum operational efficiency and minimum complexity/crew time are apparently the primary goals (as opposed to minimizing propellants used for chilldown). However, definition of charge/hold/vent cycles that will allow achievement of these goals cannot occur until/unless orbital experience and data are acquired.

OTV LH_2 TANK PRESSURES DURING ORBITAL FILL

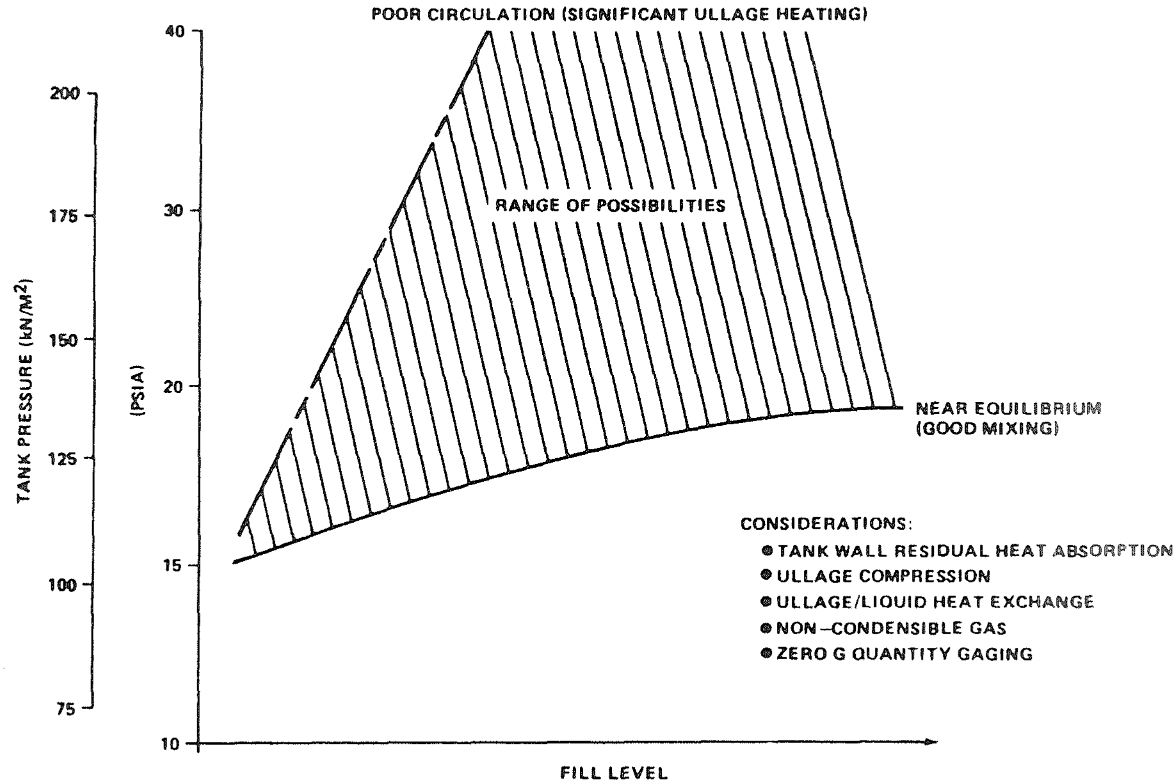


Figure 14

Assuming that the prescribed tank chilldown temperatures have been achieved, then the nonvented fill procedure can be initiated. However, care must be taken to assure that venting is not necessitated by excessive pressure during fill. Good mixing must occur throughout the fill process to prevent excessive heat transfer to the ullage and corresponding pressure increases. Additionally, tank wall residual heat absorption/distribution, ullage compression, noncondensible gases, and the measurement of transferred mass are issues that must be addressed.

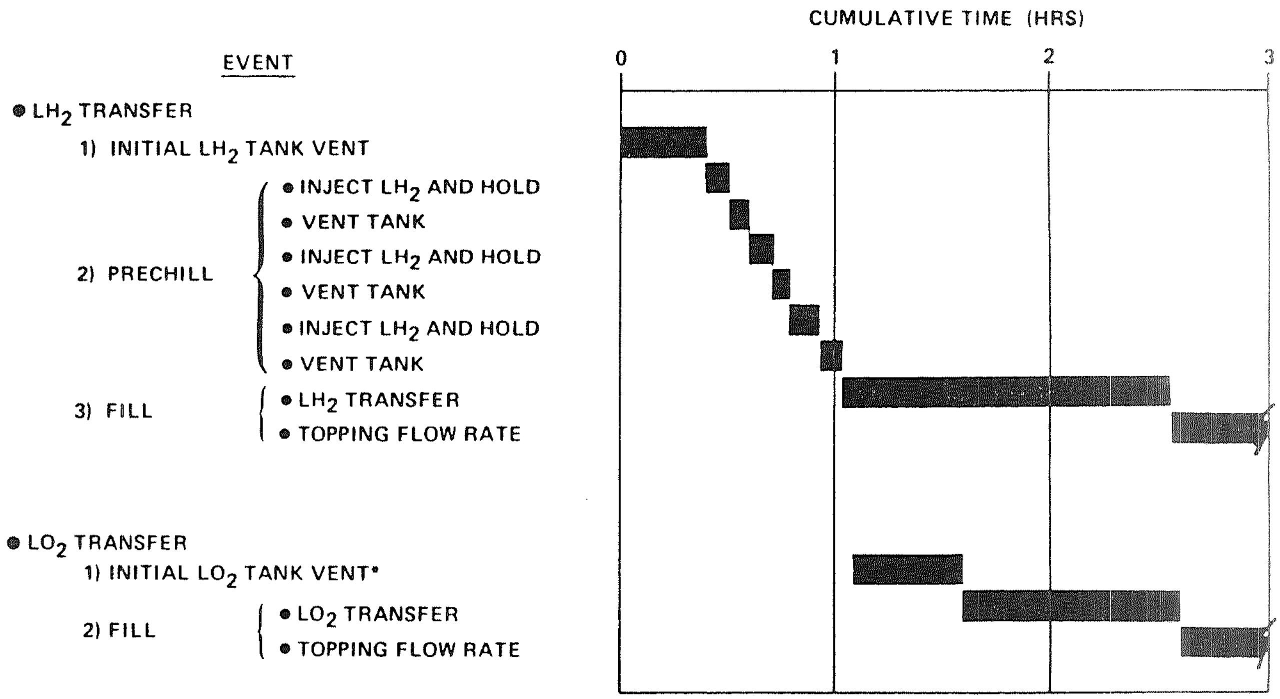
TANK FILL SUMMARY

- REQUIREMENT: LH_2 & LO_2 TANK FILL WITHOUT VENTING
- PROCEDURAL/TECHNOLOGY CONCERNS:
  - ASSURANCE OF ADEQUATE CIRCULATION TO MAINTAIN NEAR-THERMAL EQUILIBRIUM, i.e., LOW PRESSURES
    - GOOD MIXING/HEAT EXCHANGE BETWEEN ULLAGE/LIQUID REQUIRED
    - EXISTING SEMI-EMPIRICAL MODELS LACK EXPERIMENTAL DATA
    - LACK OF IN-FLIGHT HARDWARE EXPERIENCE
    - MECHANICAL MIXER PROBABLY REQUIRED
  - LACK OF ZERO-G MASS GAUGING DEVICE
  - SPECIAL FILL PROVISIONS FOR START BASKET
    - BLEED LINE FOR DIRECT FILL OF BASKET
    - ACTIVE CIRCULATION TO ASSURE ENTRAPPED VAPOR COLLAPSE
  - SUPPLY TANK VAPOR PRESSURE $\leq$ 2.2 kN/M^2 (15 PSIA), NO HELIUM PASSAGE ALLOWABLE
  - PREVENTION OF EXCESSIVE TRANSFER LINE LOADS

Figure 15

Semi-empirical modeling of the fill process is required to define the interacting fluid and thermal phenomena; however, existing models lack experimental verification. Active mixing probably will be required to assure near equilibrium thermodynamic conditions. The lack of a zero G quantity gauge is a significant handicap in achieving a 97% fill condition. Special considerations are involved in interfacing with capillary start baskets to assure that vapor entrapment does not occur during tank fill. Also, supply vessel conditions must be controlled to prevent excessive vapor pressures and the transfer of helium into the OTV.

OTV PROPELLANT TRANSFER TIMELINE



NOTE:
* TWO OR MORE ADDITIONAL VENT CYCLES REQUIRED IF HELIUM PRESENT

Figure 16

Definition of the transfer timeline cannot be accomplished with confidence until orbital experience and data become available. However, the sequence of events can be established with reasonable confidence. Based on current models, the total transfer time is expected to require on the order of 3 hours.

MSFC CRYOGENIC MANAGEMENT BREADBOARD

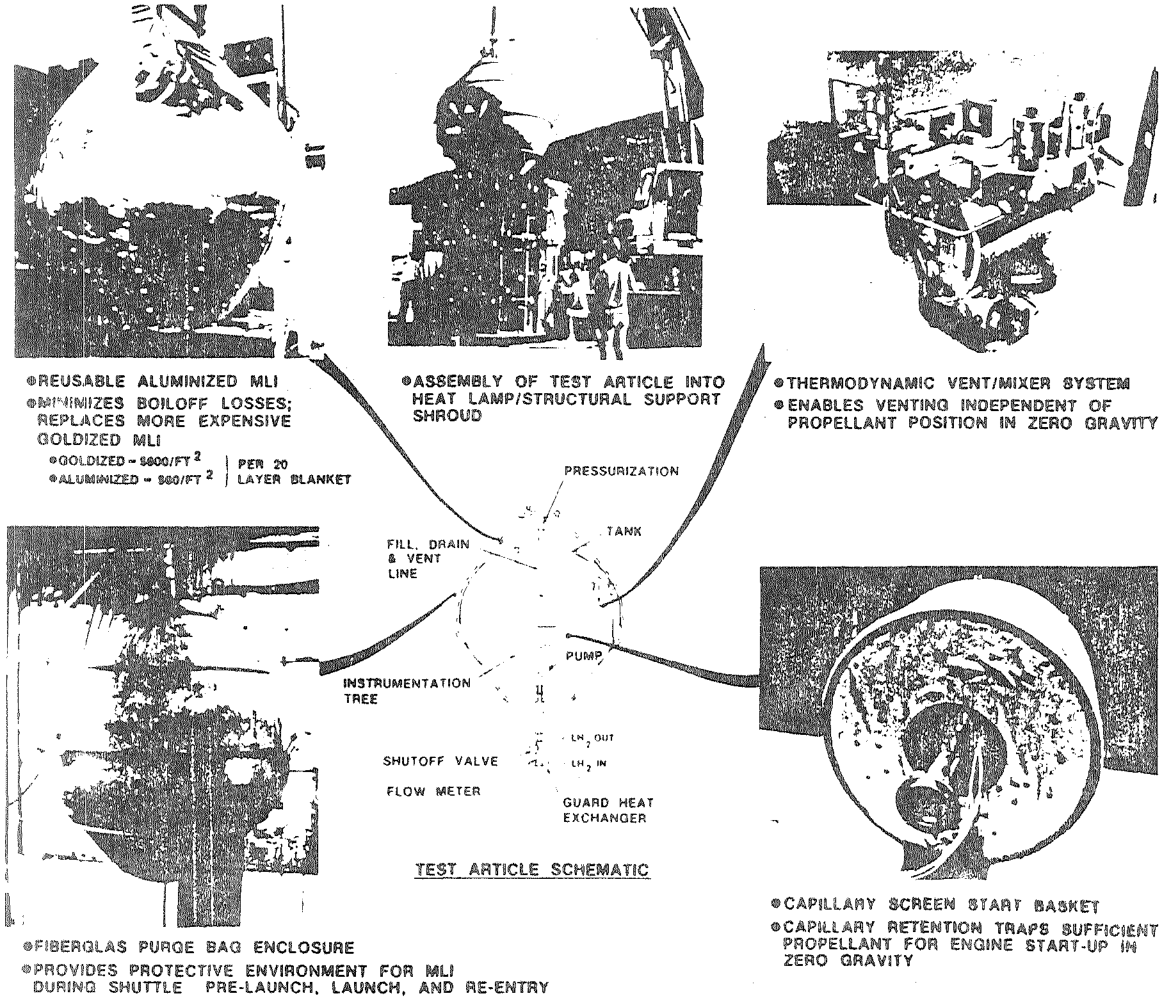


Figure 17

Various degrees of technology development are associated with the types of subsystems that will be required in an OTV cryogen management system, i.e., the technology backgrounds range from substantial to meager. However, these subsystems have never been integrated into a total OTV-type system and required to perform simultaneously. Therefore, a major objective of the cryogenic management breadboard program is to integrate advanced technology items into a system level LH_2 test article, thereby enabling evaluation of thermodynamic, heat transfer, and fluid mechanic interactions/controls/instrumentation within the limits of normal gravity testing. The breadboard data will be evaluated to determine normal gravity performance and to more specifically identify technology gaps/concerns that must ultimately be assessed with orbital experimentation, i.e., breadboard testing of this type is a prerequisite to the eventual experimental verification of OTV-type systems in orbit. Additionally, the system level experience will minimize the development risk of orbital cryogenic management experiments/flight systems in general.

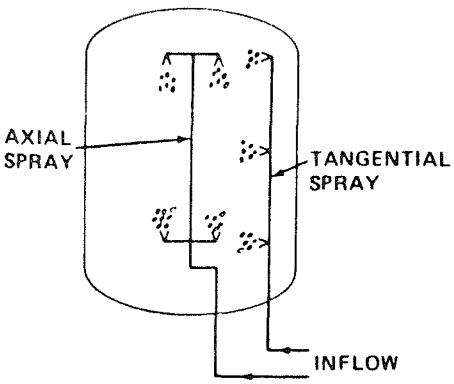
The test article tank is an 88-inch diameter oblate spheroid with a 175 ft^3 volume. The test article contains all the basic elements of an earth-based OTV LH_2 system, i.e., a reusable multilayer insulation/purge bag system, zero gravity thermodynamic vent/mixer, GH_e/GH_2 pressurization, capillary start basket, and a pump/feedline system. The multilayer insulation, organically coated aluminized Kapton, was developed to replace the more expensive reusable goldized Kapton insulations. This breadboard installation represents the first system level demonstration of the aluminized insulation for cryogenic applications.

Final preparations are in progress at MSFC for the breadboard testing. Initial LH_2 loading is scheduled for the first week of April 1984. Various test phases will be conducted intermittently through October 1984.

CRYOGENIC FLUID MANAGEMENT FACILITY
OTV TECHNOLOGY

MISSION 1

.28 SCALE
(48 IN. DIAMETER)

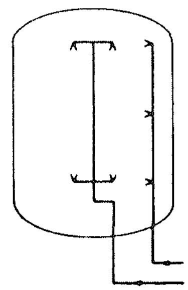


GOALS

- SCALABLE TANK CHILLDOWN DATA
- PURGED MLI (30 LAYER)

MISSION 2

.18 SCALE
(31 IN. DIAMETER)

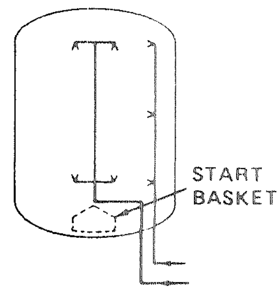


DELTA GOALS

- NO VENT FILL
- LH_2 SETTLING/OUTFLOW
- He PRESSURIZATION
- ON-WALL TVS
- STRATIFICATION

MISSION 3

.18 SCALE
(31 IN. DIAMETER)



DELTA GOALS

- START BASKET INTEGRATION & PERFORMANCE
- TVS MIXER
- FOAM/MLI COMBINATION

Figure 18

The Cryogenic Fluid Management Facility (CFMF) is expected to provide significant technology inputs to OTV development. The initial mission will utilize a .28 scale OTV LH_2 receiver vessel. Although the CFMF supply tank can fill the receiver to only about the 30% level, the primary goal of obtaining chilldown data can be achieved. An OTV representative purged multilayer insulation (MLI) will be installed on the receiver. The second mission will utilize a .18 scale vessel that can accommodate a complete fill procedure. Additional data include LH_2 settling/outflow, helium pressurization, and performance of a thermodynamic vent system (TVS) with a wall mounted heat exchanger. The third mission will also utilize a .18 scale vessel. Chilldown / fill data will again be acquired to assess repeatability of the mission 2 results. An OTV type start basket will be utilized to assess thermodynamic and fluid mechanic interface effects on start basket performance, i.e., feed system heat leak, TVS operation, and tank pressurization. The TVS may include an active mixing system. The tank insulation will consist of a foam/MLI combination.

EXAMPLE CFMF DATA FOR OTV LH_2 TANK CHILLDOWN DURING TRANSFER

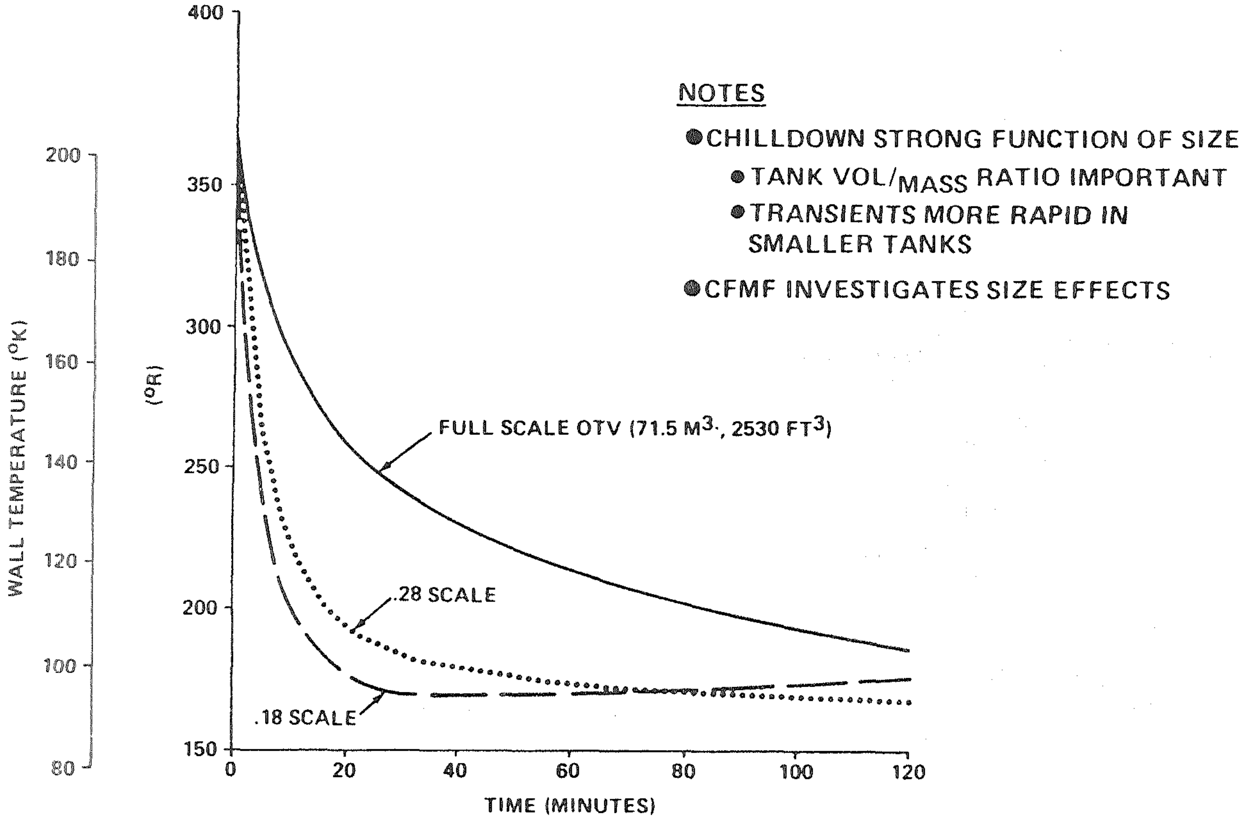


Figure 19

The relative chilldown responses of the CFMF .18, .28, and full scale OTV receivers can be illustrated using currently available analytical modeling. The smaller a vessel, the more responsive it is to heat leak and the nonequilibrium thermodynamics. This is basically because the tank volume relative to energy stored in the walls and structure becomes less with decreasing tank size. Therefore, there exists the concern that the rapid response of small vessel thermodynamics/fluid dynamics will differ significantly from the actual transients in prototype vessels. However, the CFMF design has incorporated the largest scale OTV vessel achievable (.28 scale) within the constraints of schedule and cost. Additionally, LH_2 transfer behavior in the .28 and .18 scale vessels can be compared, thereby providing valuable scaling effects data.

SPACE STATION TECHNOLOGY REQUIREMENTS
(SSTSC FLUID MANAGEMENT WORKING GROUP)

- CRYOGENIC FLUID RESUPPLY*
- NON–CRYOGENIC FLUID RESUPPLY*
- ZERO–LEAKAGE FLUID COUPLINGS
- FLUID LEAK DETECTION INSTRUMENTATION
- REUSABLE EARTH TO ORBIT CRYOGEN TRANSPORT
- FLUID QUANTITY GAUGING INSTRUMENTATION
- LONG TERM ORBITAL CRYOGEN STORAGE*
- CONTROL, INSTRUMENTATION & DIAGNOSTICS
- OPERATIONS (MANNED VS. AUTONOMOUS)
- FLUID SYSTEM STUDY

*MANDATORY FLIGHT TESTS

Figure 20

The Space Station Technology Steering Committee met in Williamsburg, Virginia in March, 1983, to discuss technology requirements and priorities. The Fluid Management Working Group recommended that technology be pursued in ten areas. The chart on the facing page lists these recommendations in order of their priority for Space Station application. Out of the ten areas, three were considered to require mandatory flight tests. These three items were considered to be enabling technologies.

SPACE STATION ADVANCED DEVELOPMENT

- ADVANCED DEVELOPMENT TEST BED
  - COMPONENT DEVELOPMENT TESTING
  - LOX/LH_2 SYSTEM LEVEL TESTING
  - FLUID LEAK PREVENTION/DETECTION
- PROPOSED SHUTTLE FLIGHT EXPERIMENTS
  - LONG TERM CRYOGENIC STORAGE FACILITY
  - REFRIGERATION/RELIQUEFACTION
  - REMOTE CONTROLLED OR AUTOMATED PROPELLANT SERVICING
- PROPOSED SPACE STATION TECHNOLOGY DEMONSTRATION MISSION (TDM)
  - PROPELLANT TRANSFER, STORAGE & RELIQUEFACTION
  - LONG TERM SYSTEM PERFORMANCE DEGRADATION

Figure 21

Based on the anticipated need for a cryogenic OTV at the Space Station, several proposals have been made to define the advanced development work that will be required to support such a goal. A combination of ground testing, shuttle flight testing and Space Station technology demonstration missions (TDM's) are evolving as the primary activity for achieving this goal. The opposite page provides a brief summary of the major proposed advanced development activity in the fluid management area.